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CLOUD RISE IN A DENSE NUCLEAR ATTACK. (U)
AUG 78 F L ADELMAN, R J SULLIVAN, J C KRUPP DNA001-77-C-0303
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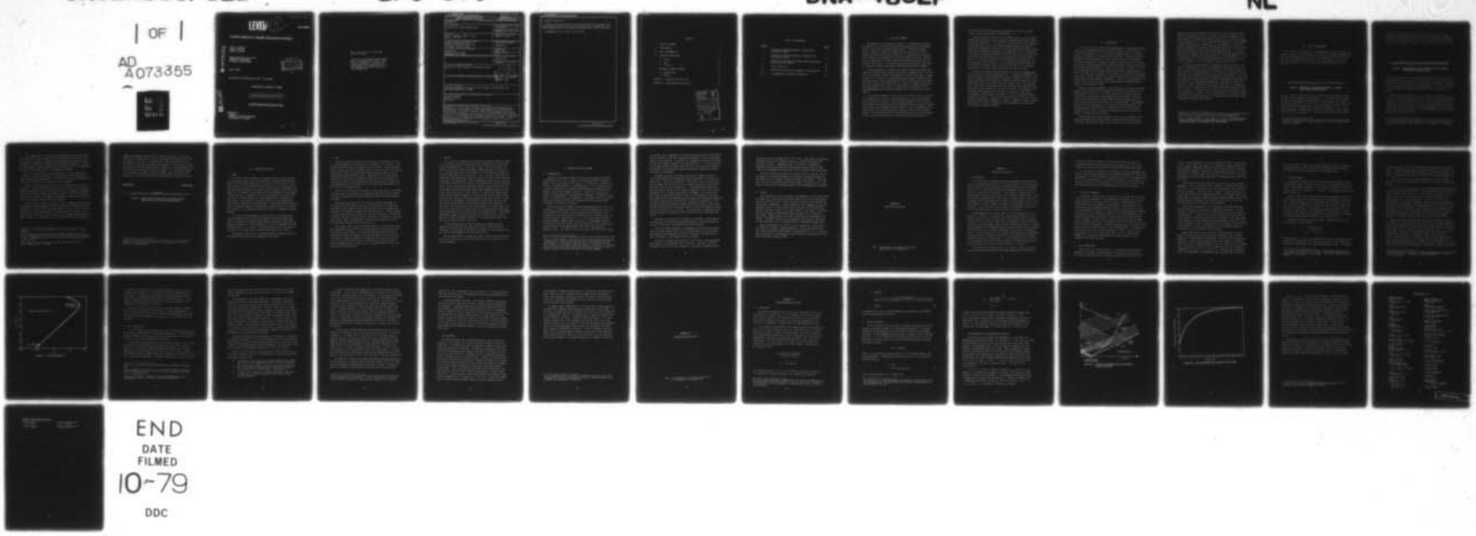

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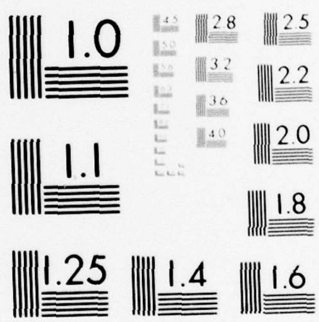
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CLOUD RISE IN A DENSE NUCLEAR ATTACK

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August 1978

Final Report for Period 20 July 1977 - 31 July 1978

CONTRACT No. DNA001-77-C-0303

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DNA 4862F	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CLOUD RISE IN A DENSE NUCLEAR ATTACK		5. TYPE OF REPORT & PERIOD COVERED Final Report 20 July 1977-31 July 1978
		6. PERFORMING ORG. REPORT NUMBER SPC 370
7. AUTHOR(s) Frank L. Adelman, Joseph C. Krupp, Roger J. Sullivan		8. CONTRACT OR GRANT NUMBER(s) DNA001-77-C-0303
9. PERFORMING ORGANIZATION NAME AND ADDRESS System Planning Corporation 1500 Wilson Boulevard, Suite 1500 Arlington, Virginia 22209		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS N99QAXAA111-15
11. CONTROLLING OFFICE NAME AND ADDRESS Headquarters Defense Nuclear Agency Washington, D.C. 20305		12. REPORT DATE August 1978
		13. NUMBER OF PAGES 38
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; unlimited distribution.

622 04H

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This work sponsored by the Defense Nuclear Agency under RDT&E RMSS code B342077464 N99QAXAA11115 H2590D

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Nuclear explosions
Nuclear cloud rise
Multiburst

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The behavior of the nuclear cloud that would emerge after the simultaneous detonation of a large number of closely spaced megaton-class detonations has been examined. The initial adiabatic expansion to approximate pressure equilibrium and the subsequent rise of the cloud as the edge effects permit buoyant forces to lift the heated air were looked at with the aid of analytic calculations and analysis of two-dimensional hydrodynamic computer calculations. The use of existing programs for estimating fallout from such a nuclear cloud was also addressed. (Continued over)

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20. ABSTRACT (Continued)

The most important conclusion is that superposition does not come close to predicting the nuclear cloud stabilization altitude or configuration, nor is that technique useful for predicting postattack winds or dust distribution.

Recommendations for further study are made.

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LIST OF ILLUSTRATIONS

I. EXECUTIVE SUMMARY

The purpose of this study was to examine, in a preliminary fashion, the behavior of the nuclear cloud that would develop after a concentrated nuclear attack upon an extended target complex. The specific example chosen is based on a pattern of megaton-class surface nuclear bursts so spaced that the initial nuclear fireballs do not interact, but the masses of air heated by the detonations do interact before significant cloud rise. The basic questions of interest relate to the postattack winds, dust distribution, and fallout. An obvious application of the present study would be to analyze an attack upon closely spaced hardened missile launchers.

The case examined is a hypothetical attack consisting of 10,000 simultaneous 1-MT ground bursts spaced 2 km apart on a hexagonal grid. For this case, the individual nuclear clouds begin to interact within about 1 second. By about 10 to 15 seconds, the entire heated mass reaches approximate pressure equilibrium. While nonsimultaneity (within a few seconds) and irregularities in spacing would affect the early motion, the general character of the cloud behavior over the tens of minutes that are relevant for full cloud development over the entire attacked area is not sensitive to these details.

The original intention of the study was to derive the general outlines of the behavior of the cloud, insofar as possible, from first principles. Early in the effort, however, System Planning Corporation (SPC) learned of the existence of a calculation of 64 simultaneous 5-MT ground bursts carried out at the Air Force Weapons Laboratory (AFWL) in 1971. A computer film of the results of this calculation led to improved insights into the phenomenology. Much of the SPC effort was then devoted to assessing the validity of this calculation with the aid of simpler calculations based on first

principles and to determining how to extrapolate the results to other yields, spacings, and numbers of detonations.

The most important conclusion of the present study is that one cannot approximate the results of such an attack by superposition of the effects of the individual bursts. The heated air rises more slowly than superposition would suggest; the cloud rises considerably higher than would be predicted by superposition; there will be very high-velocity winds at times much later than would be predicted by superposition; the size and spatial distributions of particulate matter within the cloud after cloud stabilization do not resemble those derived from superposition; and the fallout pattern will be quite different from that resulting from superposition of the individual fallout patterns. All of these observations (except possibly the first) may have significant direct military or civil-defense implications for target systems that qualify for such an attack.

After an introductory chapter (Chapter II), the basic phenomenology of the cloud rise is described (Chapter III). Although the geometry of the attack and the early-time physical configuration suggest that much of the cloud development can be treated by considering vertical motion only, this expectation proves to be correct only for the early phase of cloud expansion. After about 15 seconds, the vertical motion of the cloud slows down considerably, and, indeed, the time scale for vertical cloud motion is so long that radial motions play a key role in cloud rise. Under these circumstances, unfortunately, the analysis of cloud rise requires large computer calculations. The conclusions derived from a few of these calculations are described in Chapter IV. Chapter V suggests a research program appropriate for further investigation of the phenomena and effects that are pertinent to defense problems.

II. INTRODUCTION

It is important to understand the phenomenology of concentrated nuclear attacks against extended military targets or groups of military targets. In the case of an attack of one or a few nuclear weapons against an isolated target, the phenomena are reasonably well understood. One can estimate the parameters of the environment as a function of time after the detonation and thereby determine, for example, the conditions under which a surviving missile can be launched successfully after the attack, as well as the offsite fallout that can be expected as a result of the attack. Similarly, if there are a large number of such targets and the targets are far enough apart so that the nuclear bursts intended for one target do not interact significantly with those for another target until after the nuclear clouds have stabilized, these attacks may be treated as independent. Under these circumstances, the overall effect of such an attack may be approximated by superposing the effects of the individual bursts.

There are, however, extended military complexes in which the individual targets are sufficiently close together that the bursts do interact in the early stages of cloud rise. It is the purpose of this paper to describe investigations initiated by System Planning Corporation (SPC), under contract to the Defense Nuclear Agency (DNA), into the phenomena associated with a massive nuclear attack against such a target complex. The immediate objective of the investigation is to describe the dust distribution, the postattack winds, and the fallout associated with the many interacting nuclear bursts in order to provide a sound technical basis for decisions related to relevant military systems.

Although there have been statements to the contrary, fundamental considerations suggest that the dust from a massive interactive attack will rise higher than one would expect from a single burst, as the individual

nuclear clouds from the separate bursts are constrained laterally by the presence of neighboring clouds. As a result, the primary mechanism for cloud expansion to thermal and mechanical equilibrium is vertical movement. On an a priori basis, it is also clear that the winds will be significantly different from those of a single burst, as the difference in cloud rise behavior between the isolated and the interactive bursts will be reflected in entirely different flows of both heated and ambient air. For similar reasons, one can expect the fallout from a massive closely spaced attack to be noticeably different from that estimated by simple superposition.[1] All of these effects will be discussed further below and are treated in more detail in Appendix A, which is based on a previous SPC report.[2]

For the sake of concreteness, a hypothetical attack of 10,000 simultaneous 1-MT ground bursts on a 2-km hexagonal grid was taken as the base case. Neither the simultaneity nor the uniformity of spacing affects the applicability of the base case analysis to a practical situation. For the base case, cloud interactions can be expected to begin within 1 second, and an irreversible adiabatic expansion to approximate pressure equilibrium will take about 10 to 15 seconds (see Appendix B). Variations in spacing or timing will affect the early motion to some extent, but will average out, with only minor irregularities, by the time of pressure equilibrium; they will not affect, in a major way, the cloud behavior over the many hundreds of seconds that are relevant. Even a rolling attack on a militarily appropriate time scale would show many of the features that would develop from a simultaneous uniformly spaced attack.

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[1]Work on the validity of superposition has recently been conducted at Science Applications Incorporated (J. Moulton, DNA, private communication).

[2]Frank L. Adelman, Joseph C. Krupp, Roger J. Sullivan, Preliminary Examination of Cloud Rise in a Dense Nuclear Attack--Phase A, System Planning Corporation, Report 334, November 1977, UNCLASSIFIED.

III. BASIC PHENOMENOLOGY

It is clear from the geometry of the attack and from the relatively low speed of sound that, if the nuclear bursts interact, the major mechanisms for distributing the energy from the bursts must operate in the vertical direction for a considerable period of time. An early stage of the process is depicted in Figure 1.[1] In this figure, the thickness of the solid line

FIGURE 1. ENVELOPE OF CLOUD APPROXIMATELY 1 SECOND AFTER SIMULTANEOUS ATTACK

represents, approximately to scale for the base case, the envelope of the air mass initially heated by the detonations. The diameter of this heated air mass is about 200 km, and the height of the individual bursts, about 1 second after detonation, is close to 1 km. The heated air thus forms a thin layer, which can be treated, to a first approximation, as uniform. This layer then begins to expand adiabatically, as its pressure is much higher than that of the surrounding air. The air mass can expand only vertically,

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[1] In this and the subsequent figures, as well as in the calculations, earth curvature is ignored, as it is not important at the level of approximation used in this report.

except near the edges of the hot disc. As a result, when the air has expanded to approximate pressure equilibrium with the ambient atmosphere, the cloud top reaches about 3-1/2 km in 15 to 30 seconds, and its envelope is much like that shown in Figure 2. The early time motion is similar to

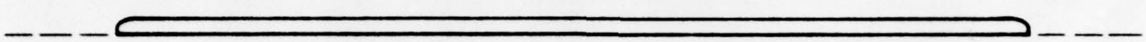

FIGURE 2. ENVELOPE OF CLOUD APPROXIMATELY 30 SECONDS AFTER SIMULTANEOUS ATTACK

that of a high-pressure gas in a shock tube after the sudden removal of a bounding membrane. While the detailed distribution of energy throughout the cloud will depend on the precise spacing and simultaneity of the detonations, the expected variations in these parameters will make the approximation of uniformity more appropriate in practice than in the base case itself.[1]

Since the anticipated cloud rise is a few tens of kilometers at most, it is reasonable to expect the rise of the cloud from the stage shown in Figure 2 to its ultimate stabilization altitude to be essentially a one-dimensional (vertical) process. This does not happen, however, primarily because there is no significant net vertical (buoyant) force on any portion of the cloud until the ambient air from the cloud edge has moved in underneath that portion of the cloud.

[1]In a practical attack, shock interactions will not reinforce precisely. As a result, the sharp discontinuities in the heated air that one calculates for the case of perfect simultaneity and spacing will be smoothed.

Taylor instability is the only other mechanism by which the hot cloud can rise before arrival of ambient air from the edges of the cloud. While this process is expected to produce isolated plumes, the plumes will most likely not rise above the single-burst stabilization altitude (~12 km), nor will they produce a general expansion of the nuclear cloud. This phenomenon requires further study, however, as suggested in Chapter V.

Early in the SPC effort, it was learned that, in 1971, AFWL had used the SHELL OIL[1] code to calculate the cloud behavior for 64 simultaneous, closely spaced 5-MT ground bursts.[2] For ease of calculation, the individual bursts were grouped into four concentric rings of energy.

Analysis of this calculation by SPC led to improved insight into the behavior of the cloud after its initial rise. As a result of this analysis, calculations based on first principles were made in an attempt to determine both the validity of the AFWL calculation and how to extend the results to other yields, spacings, and numbers of detonations. Additional calculations were also carried out at the AFWL at SPC request.[3]

As a result of the AFWL calculations and the subsequent SPC calculations and analysis, the development of the nuclear cloud in the base case can be visualized as follows. After the stage shown in Figure 2, cool air from the edges works its way underneath the cloud towards the cloud center. As it does so, those portions of the cloud with cool air beneath become buoyant and begin to rise. This process forms a saucer-shaped cloud, which gradually

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[1]SHELL OIL is a detailed multidimensional Eulerian hydrodynamic computer program.

[2]This information was provided by LTC W. Whitaker (DARPA, previously at AFWL). A computer film of the results was loaned to SPC by Mr. C. Needham of AFWL. Unfortunately, this film is the only available documentation of the calculation.

[3]These calculations were carried out at AFWL under the direction of MAJ G. Ganong and Mr. C. Needham.

deepens as the edges rise and cool air penetrates further. In 20 to 30 minutes (for the base case),[1] the cool air reaches the center of the cloud and rushes up vertically. The high-velocity winds associated with this process will raise the cloud rapidly and transform it into a gigantic torus. The toroidal cloud slows and ultimately flattens as it approaches stabilization altitude (on the order of 30 km or higher). The torus has an overall radius noticeably (perhaps 30 percent) greater than that of the initial attack area. The final cloud will look approximately as shown in Figure 3.

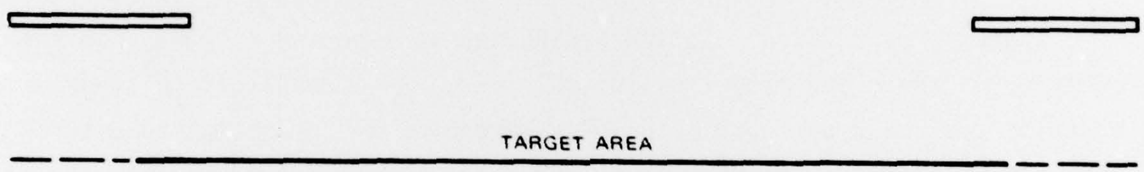

FIGURE 3. ENVELOPE OF CLOUD ABOUT 30 MINUTES AFTER SIMULTANEOUS ATTACK (VERTICAL SECTION)

[1]In general, the precise time of arrival of the cool air at the center will depend on the energy density deposited in the attack and on the linear extent of the attacked area.

IV. TENTATIVE CONCLUSIONS

A. WINDS

The picture given in Chapter III suggests that the winds associated with the massive attack under discussion in this study will be similar to those of the individual detonations for perhaps 10 to 15 seconds. Afterwards, there will be a period of relative calm, which will terminate with very high-velocity winds as the cool air from the edge of the affected area moves in. The highest velocity winds will be associated with the formation of the large torus. Because it will take on the order of 30 minutes for the cool air to reach the center of the attacked area in the base case, high winds will not appear in the central portion of the attacked area until tens of minutes after the detonations. Significant winds will appear earlier towards the edge of the area and *will persist for tens* of minutes. This result is very different from that which would be expected from superposition.

It is clear from the preceding description that the period during which high winds may be found can be reduced by making the target area smaller. Because, for constant energy density, the pressure differential between the ambient air and the heated air is virtually independent of the attacked area (if it is large), the time at which the high winds appear at the center of the target area is roughly proportional to its radius.

The intensity and duration of the winds produced immediately outside the attacked area have not been addressed in this study.

B. DUST

The dust from the individual 1-MT ground burst is expected to rise to an altitude between 4 and 12 km and will not generally rise further in any particular locality until the edge effects arrive there. Before the edge effects arrive, the dust will appear in more or less toroidal rings centered on the burst points, but, being confined by neighboring bursts, will be concentrated between the burst points. Upon arrival of the edge effects, the dust will be carried to higher altitudes and, after the outside air reaches the center of the attacked area, will form into a very large torus located generally at an altitude of 30 to 40 km and concentrated near the outer edge of the attacked area.

The rise to stabilization altitude will take on the order of 30 minutes (from the start of the attack), and, because of the inertia of the heated air mass, the cloud will not move laterally very much for perhaps another 30 minutes.

While each individual burst will tend to raise the same amount of dust from the cratered area as would an isolated burst of the same yield, the amount of dust drawn into the cloud from the rest of the neighboring surface will be limited by competition from other bursts. Further, because it takes so long for the cloud to start its main rise phase, a significant fraction of the dust in the cloud will fall back to the ground at relatively early times. Some of that material, however, may be swept back up into the cloud when the edge effects finally arrive.

While there remain significant uncertainties as to the precise amount and characteristics of the dust (including specifically how high the dust will rise at early times), it is clear that the dust effects cannot be estimated reliably by superposing the dust distribution of the individual 1-MT bursts. Under the assumption of superposition, the dust would tend to rise to about 12-km altitude in 5 minutes and then spread laterally with the ambient winds; it would not go to the much higher altitudes suggested by the present model.

C. FALLOUT

For a variety of reasons, the fallout from a massive interactive attack will be different from that estimated by the superposition of 10,000 individual 1-MT ground bursts. First, the cloud will take a relatively long time to rise to stabilization altitudes. Second, because of its mass, it will accelerate very slowly in the ambient air field, taking 30 minutes to 1 hour to reach ambient wind velocities. Third, the delay of the start of significant cloud motion means that the fallout will arrive later than would be predicted by superposition, with correspondingly lower fallout radiation fields at the time of arrival because of the additional time for radioactive decay. Fourth, the amount and size distribution of the entrained dust will be different from that which would result from independent bursts, as many of the larger particles will have time to fall out over the attacked area, rather than be deposited downwind. Finally, because of the rather different early-time history of the nuclear cloud and the early fallout of large dust particles, the number of dust particles in the cloud and their size distribution at the time of solidification of many of the radioactive species will be quite different from those observed in a single burst, with the likely result that the radioactivity will be concentrated on particles smaller than would be found in the case of independent bursts. These latter two features suggest that the fraction of the offsite fallout that will appear as distant or worldwide fallout will be significantly larger than that usually associated with 1-MT bursts.

If the single target area were divided into a number of smaller separate target areas with the same attack density, the offsite area affected by fallout would be expected to be larger, as cloud stabilization and lateral cloud movements would both occur earlier.

None of these effects has been calculated in detail, and a significant effort will be required, as will be discussed below, to quantify the preceding statements.

V. SUGGESTED RESEARCH PROGRAM

A. PHENOMENOLOGY

Because of the possible impact on the design or operational control characteristics of military systems that may be subjected to a massive attack of the type treated in this study, it is important to determine the validity of the description of the phenomenology. This can best be done by using a combination of a few sophisticated computer calculations; for example, the Air Force Weapons Laboratory's (AFWL) HULL[1] program, and simpler analyses based on more approximate approaches. The purpose of the latter is to ensure that, in the absence of experimental data for verification, the results of the more complicated calculations are not unduly influenced by mathematical artifacts.

There are two basic computer calculations required at this time. One of these is to calculate the motion of a uniformly heated disc of air 1 km high and about 8 km in radius containing about 60 MT of energy.[2] This calculation is much simpler than a calculation of 60 individual bursts, as it can be done by a two-dimensional (i.e., radius and height variables, assuming azimuthal symmetry) HULL calculation. The phenomena should be calculated for about 600 seconds after the detonation, at an expected cost of about 20 hours of CDC 6600 computer time, plus a few man-days of preparation time. The results of this calculation, which has been started

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[1]HULL is a sophisticated hydrodynamics program currently operational at AFWL.

[2]This is an approximation to the AFWL 60- and 61-burst escalations discussed in Appendix A. A calculation of 60 individual, simultaneous, uniformly spaced bursts is not only more difficult, but it is also less realistic, as, in practice, such symmetry cannot be achieved. Eventually, as indicated below, a calculation of many individual bursts should be made, but care should be taken in that calculation to avoid precise symmetry.

by the AFWL, will be compared with similar HULL calculations (with different initial conditions) that have already been completed, to see if the general behavior is as expected. It should also be compared with simple calculations on the rate of radial movement of the cool ambient air. If the calculations do not agree, additional simple calculations will be required to determine the reasons for the disagreement before further HULL calculations of this type would be recommended.

A second, more complicated HULL calculation is needed to ensure a proper understanding of the phenomena before the ambient air arrives at a given point. The current assumption is that there is very little gross air motion between the time of the initial adiabatic expansion of the air and the time of arrival of the ambient air. A three-dimensional calculation should be made of the motion of a square or hexagonal cell 2 km on a side, containing 1 MT of energy, appropriately distributed. This calculation would describe the general motion of the air in the middle of the cloud. The calculation must be three-dimensional, rather than azimuthally symmetric, in order to observe more realistically the growth of instabilities. This calculation would also provide insights regarding the amount of dust swept up into the cloud and the cloud conditions at the time the radioactive atoms solidify onto particles in the cloud. The calculation is expected to take several man-weeks of preparation time and about 40 hours of CDC 6600 time to run.

An analysis of the results of these two calculations, extrapolated to the base case, would provide a reasonable estimate of the gross characteristics of cloud rise, wind patterns, and dust distribution.

Only after these calculations are understood should a unified calculation of the base case be made. This calculation would be a large effort and should not be undertaken before one is reasonably confident that the tools available will give answers that are credible.

In order to increase the credibility of the results, some experimental verification of the phenomena would be desirable. Devising a practical experiment is a difficult task, however, as a realistic experiment must be

scaled by a factor of perhaps 10^9 to 10^{12}. Over so many orders of magnitude, the credibility of the extrapolation may be no better than that of the original calculation. Nonetheless, one can conceive of experimental approaches (such as exploding wire techniques) that may be able to shed light on the phenomena, and some effort in this direction would be desirable.

Since the idealized base case will never be found in practice, it will be necessary to analyze the effects of deviations in space and timing and the impact of a small number of weapon failures on the analysis. This step may or may not be possible without large computer calculations, but, in any event, it should not be undertaken before a basic understanding is achieved.

B. FALLOUT

The calculations needed to evaluate the magnitude of the fallout problem associated with a massive attack and the impact of the size of the attacked area on the offsite fallout situation can best be done with the DELFIC code, as discussed in Appendix A. A major measure for this statement is that the assumption implicit in most simpler fallout programs--that the horizontal motion of the fallout cloud is the same as that of local winds--is not valid. The fallout impact can be estimated from the results of the cloud rise calculations suggested above to provide a relatively early estimate of the effects. The DELFIC calculation is expected to require about 2 man-months of input preparation work, plus about 50 hours of CDC 6600 computer time.

After the phenomena for the base case are determined, a second DELFIC calculation can be made if deemed appropriate. While a good calculation for a smaller target area would require a separate DELFIC run, it is possible that the effects can be estimated by careful analysis of the results of the other calculations suggested above.

Appendix A

ANALYSIS OF CLOUD RISE

Note: This appendix is an updated and slightly modified form of SPC Report 334.

Appendix A

ANALYSIS OF CLOUD RISE

A. INTRODUCTION

If a large number of megaton-class nuclear weapons were surface-burst nearly simultaneously and essentially uniformly spaced in a relatively small area, the behavior of the nuclear cloud and debris would be very different from that of a single nuclear detonation corresponding either to the total yield or to the yield of one weapon. In the case of a single burst, the cloud expands rapidly to form a more or less spherical heated volume. Since the heated volume expands by a large factor to produce a ball of gas much less dense than the surrounding air, there is a large buoyant force to lift the heated air to high altitude. A variety of other processes go on as the heated air rises, forms into a torus, cools, and ultimately stabilizes at an altitude on the order of 10 to 15 km (for a 1-MT burst).

The phenomenology for a large number of closely spaced bursts is, of necessity, different. If the bursts are close enough together, as in the present study, the clouds interact, even if the fireballs do not, before the cloud can rise very far. Under these circumstances, the early adiabatic expansion of the air heated by the individual nuclear detonations is limited by the presence of the neighboring bursts, and more vertical than horizontal expansion takes place. Even more important, after the initial expansion, there is no body of dense cool air surrounding the heated air, and therefore no buoyant force to provide a large vertical acceleration after the early pressure equilibrium is established. It would therefore not be surprising if the subsequent behavior of the nuclear debris is vastly different from that associated with a single nuclear detonation of any yield.

The purpose of the present study is to attempt to understand how the nuclear cloud formed by the near-simultaneous detonation of many closely

spaced nuclear weapons behaves. Possible applications of the results include evaluation of the postattack winds and comparison of the fallout patterns from concentrated attacks with those of more widespread attacks.

For the sake of concreteness in understanding the basic phenomena, the initial calculations are based on the simultaneous detonation of 10,000 1-MT ground bursts in a 200-km-diameter hexagonal pattern with 2 km between bursts, with earth curvature ignored. Analyzing the sensitivity of the results to the precise timing and spacing appears, at this time, to be far less important than obtaining an initial understanding of the basic phenomena.

B. THE INITIAL EXPANSION

The original intention was to treat much of the cloud rise in the ballistic fireball approximation. The condition for such behavior is that the available energy be distributed over a horizontal region comparable in linear dimension to an atmospheric scale height, a condition that is certainly met by the hypothesized detonation pattern. The altitude to which the cloud expands ballistically in this infinite plane case can be estimated by assuming a vertical adiabatic expansion in a uniform atmosphere corresponding to the pressure and density at the top of the initial fireballs (~1 km altitude). The equilibrium is not with the pressure that an exponential atmosphere would have at the height to which the cloud rises, as, in effect, the entire atmosphere is raised by the expansion of the nuclear cloud. On the assumption that 80 percent of the detonation energy is available for the expansion, the initial cloud temperature is 1570°K. The cloud then rises to about 3.5 km in a time on the order of 10 to 15 seconds (see Appendix B). The ballistic approximation thus describes only a small fraction of the total cloud rise.

C. WHAT HAPPENS NEXT?

For the rise of a single fireball, as indicated above, the adiabatic expansion is followed by a buoyant phase in which the hot gas rises as a unit through the cooler ambient atmosphere, expanding and cooling in the

process. In the approximation of an infinite plane layer of hot gas underlying a cooler, denser gas, however, the approach to thermal equilibrium must come about through dissipation of the energy by radiative, conductive, or convective processes. Radiation is easily shown to be slow, as a black body radiating at 1570°K would lose less than 10^{-4} MT/sec/km^2. Conduction through the air would be about two orders of magnitude slower for the times of interest.

Convective processes are related to instabilities in the disturbed atmosphere. Since, during and after the adiabatic expansion of the hot air, the hot gas is at a lower density than the overlying cool gas, the layers are Taylor unstable. As will be seen in Section D, Taylor instability on a scale appropriate to the temperature and density differences that one can expect after the adiabatic expansion does not proceed rapidly. Many minutes can be expected to elapse before the nuclear cloud finally comes into thermal equilibrium with the rest of the atmosphere.

Under these circumstances, it is important to determine what other physical processes may take place on a comparable time scale. The most important of these, for the case of 10,000 1-MT bursts with 2-km spacing, is edge effects. In spite of the fact that the radius of the hot disc is large (~100 km), the times for cool air to move under the hot cloud appear to be comparable to those required for one-dimensional (vertical) dissipation of the nuclear cloud. Edge effects will be treated in Section E below, in the context of discussion of some past Air Force Weapons Laboratory calculations and high explosive (HE) experiments.

Edge effects dictate that the results of HE experiments or hydrodynamic code calculations cannot be scaled to higher yields, different spacings, or larger numbers of detonations. Each case must be calculated separately. The time at which edge effects can influence a significant portion of the area involved depends on the linear dimensions of the cloud. Since the velocity at which air from the edge can move into the center is independent of the scale of the bursts (for a fixed hot gas temperature), small scale experiments and calculations that show edge effects dominant

at relatively early times, such as those described in Section E below, do not guarantee that, on the 100-km scale, other effects do not influence the cloud rise before the edge effects have become dominant.

D. TAYLOR INSTABILITY

The adiabatic expansion of the cloud ignores buoyant effects. After the expansion, there is a hot, low density gas in pressure equilibrium with a cool, higher density gas above. This situation is unstable. Since this phenomenon was first treated by G. I. Taylor,[1] it is commonly referred to as Taylor instability.

When two fluids with a common interface are accelerated (such as in a gravitational field), any irregularities at the interface will change with time. If the more dense fluid is accelerating the less dense fluid (such as a layer of air supported by an underlying layer of water), the irregularities will smooth out. If the reverse is true, the irregularities will tend to grow, at least in the absence of surface tension. The rate of growth of the irregularities depends on their dimensions, the difference in viscosity between the two fluids, and the surface tension.

Neglecting viscosity and surface tension, irregularities grow like cosh nt, where t is the time and

$$n = \sqrt{\frac{g\ (\rho_2 - \rho_1)\ K}{(\rho_2 + \rho_1)}}\ .$$

In this equation, ρ_1 and ρ_2 are the densities of the less dense and the more dense fluids, respectively, and K is the wave number of the irregularity. The smaller the wavelength, the faster the disturbance grows. This growth

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[1]G. I. Taylor, "The Instability of Liquid Surfaces When Accelerated in a Direction Perpendicular to Their Plane, I," Proceedings, Royal Society of London, Vol. 201, Series A, p. 192, 1950.

continues predictably until the amplitude becomes comparable to the wavelength. Subsequent growth cannot be calculated analytically, because the analytic theory of Taylor instability growth is based on linearized hydrodynamic equations and loses its validity when the disturbance becomes large.

When viscosity or surface tension are important factors, growth is maximum for a particular wavelength, decreasing for larger or smaller wavelengths.

For the case of a hot gas cloud underlying the cooler ambient atmosphere, viscosity must be taken into account. The linearized theory[1] predicts a growth curve as shown in Figure A-1. Note that the wavelength which grows fastest is only 0.8 cm, which is totally irrelevant for predictions of nuclear cloud rise. For a wavelength of 2 km ($K = 3.1 \times 10^{-5}$ cm^{-1}), corresponding to the natural irregularity caused by placing the weapons on a 2-km grid, the growth rate n is approximately 0.1/sec. Since the initial amplitude of the irregularities of this wavelength can be expected to be on the order of 1 km, the linear Taylor instability theory will not apply after one e-folding time (~10 seconds) after the end of the adiabatic expansion. This time is short compared to the total cloud rise time.

Because the linearized theory does not permit a detailed calculation of the mixing of the two gases, simple calculations of further buoyant rise after the cold gas begins to penetrate the hot cannot be made. Experiments show, however, that, in general, spikes of the cold fluid will fall through the hot gas. The scale of this problem is such that these spikes could become Helmholtz unstable. One possible effect of this instability is that the cold gas will not penetrate all the way to the ground, but will form a layer within the hot gas. The bubbles of hot gas which are left could rise through simple buoyant action or could form together into a new layer, beginning the Taylor instability process anew. Each succeeding layer

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[1]See R. Bellman, and R. Pennington, "Effects of Surface Tension and Viscosity on Taylor Instability," Quarterly of Applied Mathematics, 12, Number 2, p. 151, July 1954.

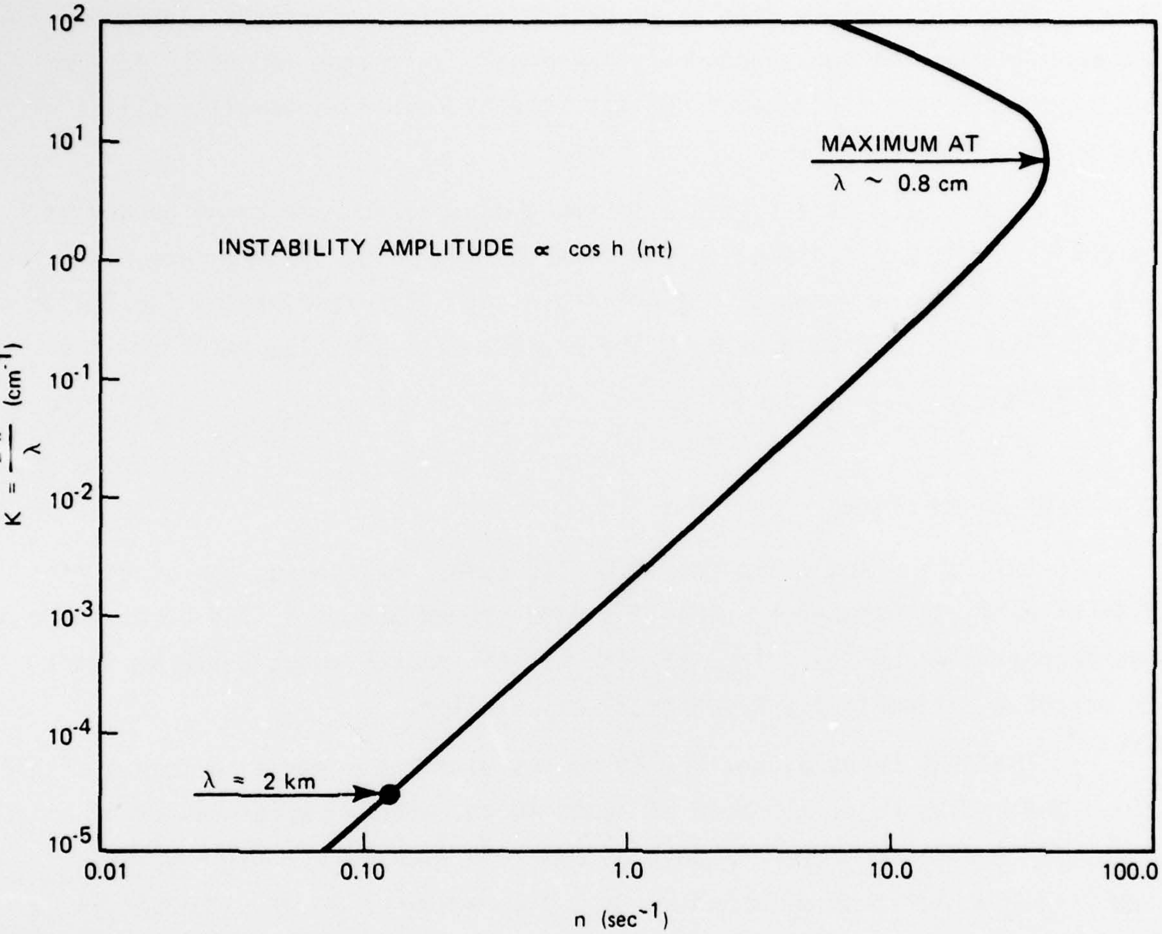

FIGURE A-1. TAYLOR INSTABILITY

so formed will be cooler than the preceding because of mixing of the cool spikes with the hotter gas. The instability will thus develop more and more slowly. By analogy with other energy transport processes, one may be able to describe the subsequent growth as a diffusion process. If the analogy holds, the distance of hot gas rise by Taylor instability will increase as the square root of the time.

Detailed calculations with existing hydrodynamic models are needed to permit accurate predictions of later events. In using these models, it will be necessary to ensure that artificial dominant wavelengths for Taylor instability are not introduced by the process of sizing the zones for the calculation.

E. AFWL CALCULATIONS

In 1971 the AFWL, using the SHELL OIL code,[1] calculated the cloud rise from 64 5-MT, simultaneous, closely spaced ground bursts.[2] The burst pattern was approximated by four rings of very hot air spaced about 2-1/2 km apart to permit a cylindrically symmetrical calculation.

In the AFWL calculation, the 64 bursts ultimately merge to form a single torus that rises to an altitude of about 40 km, with an outer radius of about 65 km. These figures should be compared with EM-1,[3] which gives a stabilization altitude of about 20 km and a radius of 30 km for a single 5-MT detonation and an altitude under 30 km and radius on the order of 100 km for a single 320-MT detonation. It appears likely that, as will be discussed

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[1]SHELL OIL is a detailed Eulerian multidimensional hydrodynamic computer code.

[2]SPC was informed of this effort by LTC W. Whitaker (formerly with AFWL, now at DARPA) and was given a film of the results through the courtesy of Mr. C. Needham of AFWL.

[3]Defense Nuclear Agency, Capabilities of Nuclear Weapons (U), Part I, Phenomenology, DNA EM-1, July 1972, SECRET/RESTRICTED DATA.

below, the combination of the 64 bursts into a single torus is an "edge effect" phenomenon and does not result directly from early time fireball interactions.

The development of the final pattern, as suggested by qualitative analysis of the film of the AFWL calculation, is extremely interesting. The initial bursts rapidly expand to pressure equilibrium, in a time consistent with ballistic fireball rise. The outer ring of hot air, being less constrained by neighboring bursts, expands to a somewhat lower density and begins to rise, while the top of the central ring actually falls somewhat. The cooler outside air pushes the outer ring towards the next ring and upwards, and air flows under the outer ring. As the air comes in, the outer ring begins to rise buoyantly, and the hot air assumes the shape of a shallow saucer. The consequent pressure reduction (and/or gas flow) permits the next ring to begin to rise and allows air to flow further towards the center; the "saucer" thus becomes deeper. Meanwhile, plumes form on the second and third rings from the outside.

At about 80 seconds after the detonation, the outside air converges on the center of the pattern. The cool high pressure air then rushes through the low density central portion of the detonation area, rises rapidly, and pushes the remaining hot gases outwards and upwards. The torus then unifies and flattens as it approaches stabilization, at about 600 seconds.

While it is not clear how to extrapolate this single calculation to the case of 10,000 1-MT bursts, the interpretation of the AFWL calculation given above suggests that:

- The behavior of the nuclear cloud cannot be described by superposing more or less independent vertical and radial phenomena.
- After the initial adiabatic expansion, the center of the cloud will rise either by long-term Taylor instability phenomena or by the inrush of air from the edge of the heated disc.
- In either case, the use of a detailed hydrodynamic code, such as SHELL OIL, is required to develop quantitative insights into the phenomena.

In order to evaluate these suggestions, the AFWL has run two similar calculations. The first was a two-dimensional calculation of 61 1-MT bursts simulating a hexagonal pattern with 2-km spacing. The energy was distributed initially in four concentric rings, with one burst at the center and an initial energy density in each ring of 10^{-12} ergs/gm. This choice of initial conditions led to the development of four essentially separate toroidal rings that did not merge until after the winds from the edge reached the center. The early behavior is quite different from that of the 64 5-MT burst calculation run previously by AFWL, but the subsequent behavior is similar. An analogous calculation, with 60 1-MT bursts (omitting the central burst), was then made by the Air Force Weapons Laboratory to eliminate the effects of the apparently anomalous behavior at the center. The results were qualitatively similar, except at the center, to those of the 61-burst calculation.

A simple model was developed by SPC to estimate the time for cool air to move from the edge of the initial cloud area to the center in this type of geometry. This model gives a time of arrival at the cloud center of about 80 seconds for the 64-burst AFWL calculation, consistent with that deduced from the computer simulation movie. The same model predicts about 1,800 seconds for the 10,000-burst case and around 150 seconds for the AFWL 60 and 61 1-MT burst calculations described above. The AFWL calculations, however, give a considerably shorter time (~90 seconds). It is not yet clear whether this discrepancy is due to the inadequacy of the simple model or to peculiarities in the initial conditions of the AFWL calculations.

The AFWL has participated in several experiments with high explosives. In one of these, six 1,000-lb (450-kg) spherical charges 70 feet (21 meters) apart were detonated simultaneously on the earth's surface in a hexagonal pattern.[1] Contrary to expectations (but consistent with the preceding

[1]With the usual factor of two used for converting HE charges to equivalent nuclear detonations, this scales to 1 MT at 7,000 feet (2.1-km) spacing, not far from the conditions of the base case considered in this paper.

description), the clouds merged into a single torus. It was also noted by AFWL that the mixing of air and detonation products was considerably more extensive than anticipated.

A second experiment consisted of six 1,000-lb (450-kg), half-buried, spherical charges spaced about 120 feet (37 meters) apart and detonated simultaneously. Preliminary observations indicate that these bursts did not interact significantly, but rather behaved much like six independent bursts. Whether the lack of interaction was due primarily to the fact that the spheres were half-buried (which would put a larger fraction of the energy into vertical motion) or primarily to the larger spacing (37 meters versus 21 meters) is not clear at the time of writing. Until this question is at least partially resolved, it will be difficult to determine to what extent these results modify the physical picture given above for the many-burst case.

F. FALLOUT MODELS

The fallout pattern from a concentrated attack, such as that under discussion in this paper, will be very different in nature from that of a single burst. While SPC has not yet examined this problem in depth, some tentative observations can be made. For example, the apparent slow early rise of the 10,000-burst cloud suggests that many of the heavier particles will not rise as far and will, therefore, fall out sooner and more nearly locally than they would from isolated bursts. Second, the very high winds that one can expect after the outside air reaches the center of the pattern will raise the smaller particles of dust and the associated nuclear debris to very high altitudes, considerably higher than those associated with single bursts. Third, the significantly higher cloud altitude means that those particles that are raised into the stratosphere will take a longer time to fall. Fourth, because of the larger extent of the combined nuclear cloud (as compared with a single burst), it will take a long time (probably tens of minutes) before the normal winds will begin to dominate nuclear

cloud movement;[1] indeed, there may well be a significant distortion of the wind fields for tens of kilometers from the edges of the affected area. Fifth, again because of the high altitude of the debris, the falling particles will experience considerable wind shear once the prevailing winds begin to dominate cloud movement.

For these reasons, among others, it is clear that one cannot sensibly estimate fallout patterns using unmodified conventional fallout codes. In particular, any code that uses an "effective fallout wind," such as WSEG-10, is not appropriate. DELFIC is an obvious choice, since it is based largely on basic physical principles. The major problem with DELFIC is its long computer running time. Since, however, much of that time is due to the cloud rise module, the use of DELFIC for the present purpose may be reasonable, as the cloud development data could be fed into DELFIC by formula from a separate hydrodynamic calculation. If this is feasible, the use of SEER, a more rapid approximation to DELFIC, would offer little advantage. Another fallout program, PROFET, may also have some utility for this problem, but DELFIC appears to be superior because of its greater flexibility.

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[1]At jet stream altitudes, for example, a 300-km/hr wind over a 3-km thick altitude band would deliver about 0.01 MT/sec to a 200-km diameter cloud created by the detonation of 10,000 MT.

Appendix B

ONE-DIMENSIONAL CLOUD RISE

Note: This appendix is a slightly modified form of the Appendix to SPC Report 334.

Appendix B

ONE-DIMENSIONAL CLOUD RISE

A. INTRODUCTION

The problem considered in this calculation is the rise of the cloud associated with the detonation of a large number of 1-MT nuclear weapons with centers 2 km apart. The purpose of this exercise is to determine those factors responsible for cloud rise which are independent of edge effects and to determine if these factors are indeed the dominant ones.

It is assumed that 80 percent of the energy released in the detonation goes into the thermal energy of the cloud. While this figure is slightly higher than occurs in a single surface explosion, much of the radiation which would normally escape from a single fireball will, in this case, be reabsorbed by the others; 80 percent thus provides a lower limit on the cloud energy.[1] The cloud height at the start of the calculations was assumed to be 1 km, approximately the fireball radius. The energy per unit volume was thus:

$$E = \frac{(0.8)\ (4.2 \times 10^{22}\ \text{ergs})}{\pi\ (10^5\ \text{cm})^2\ (10^5\ \text{cm})}$$

$$= 1.1 \times 10^7\ \text{ergs/cm}^3 \quad . \tag{1}$$

For an average density of $\rho = 1.2 \times 10^{-3}$ g/cm^3 and a molecular weight of $\mu = 29$ g/mole, this energy translates into a temperature increase of:

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[1]The initial energy density and temperature in the cloud are proportional to the percentage of the energy assumed to remain in the cloud; the height of the cloud after the initial expansion is proportional to the 0.7 power of that percentage.

$$\Delta T = \frac{E}{C_v \cdot R \cdot \rho/\mu}$$

$$= \frac{1.1 \times 10^7 \text{ ergs/cm}^3}{(5/2)\ (8.3 \times 10^7 \text{ ergs/mole/° K})\ [(1.2 \times 10^{-3} \text{ g/cm}^3)/29 \text{ g/mole}]}$$

$$= 1280° \text{K}. \qquad (2)$$

The temperature of the original atmosphere was assumed to be 15°C (288°K), so the cloud temperature is 1570°K.

B. INITIAL CLOUD RISE

In this calculation, the hot cloud is assumed to expand because of the pressure differential between it and the ambient atmosphere. No buoyancy effects are present because the air above the cloud cannot reach beneath the cloud. If the atmosphere above the cloud is assumed to have a constant density ($\rho = 1.1 \times 10^{-3}$ g/cm^3 at 1 km) and pressure (P at 2 km = 9.0×10^5 dynes/cm^2), the final height of the cloud can be approximated by assuming an adiabatic process:[1]

$$PV^{\gamma} = \text{constant}, \qquad (3)$$

where γ is the adiabatic constant, equal to 1.4 for diatomic gases at the cloud temperature. The pressure in the cloud at time t = 0 is found from the ideal gas law:

$$P = \rho RT/\mu$$

$$= 5.2 \times 10^6 \text{ dynes/cm}^2 \quad . \qquad (4)$$

Thus, the final height, h_f, is found to be:

[1]This expression is approximate because the expansion of the hot gas is not strictly reversible. The approximation will slightly underestimate the final height of the cloud.

$$h_f = \left[\frac{(5.2 \times 10^6)}{(9.0 \times 10^5)}\right]^{\frac{1}{1.4}} \times 10^5 \text{ cm}$$

$$= 3.5 \text{ km} \quad . \qquad (5)$$

A density and pressure corresponding to those atmospheric values at the initial cloud top (1 km) is used in the above calculation, rather than those values associated with an exponential atmosphere, because the underlying cloud is assumed to be so large that the entire atmosphere is raised; i.e., the expansion takes place in times short compared to the influx of air from the edges, so the atmosphere has no time to adjust.

C. TIME DEPENDENCE OF ONE-DIMENSIONAL CLOUD RISE

To determine the approximate time dependence for cloud rise, the atmosphere was considered uniform, as stated above. In this case, the situation corresponds to the case of a semi-infinite shock tube with a high-pressure, high-temperature gas on the left side of a membrane and a low-pressure, low-temperature gas on the right. When the membrane is broken, the hot gas expands into the cold and the motion of the boundary between the two gases can be determined by considering in detail the shock wave entering the cold region and the rarefaction wave entering the hot region. The motion is as shown in Figure B-1. Figure B-2 shows the motion of the cloud-atmosphere interface in the present case. This calculation is described below.

Initially, a cloud of hot gases at temperature T_c, pressure P_c, and density ρ_c is located at the surface of the earth. The cloud is assumed infinite in extent with a thickness L. The atmosphere above the cloud has a temperature T_a, pressure P_a, and density ρ_a. There is a discontinuity in temperature, pressure, and density across the interface, with $T_c > T_a$, $p_c > p_a$, and $\rho_c > \rho_a$. Curvature of the earth is ignored.

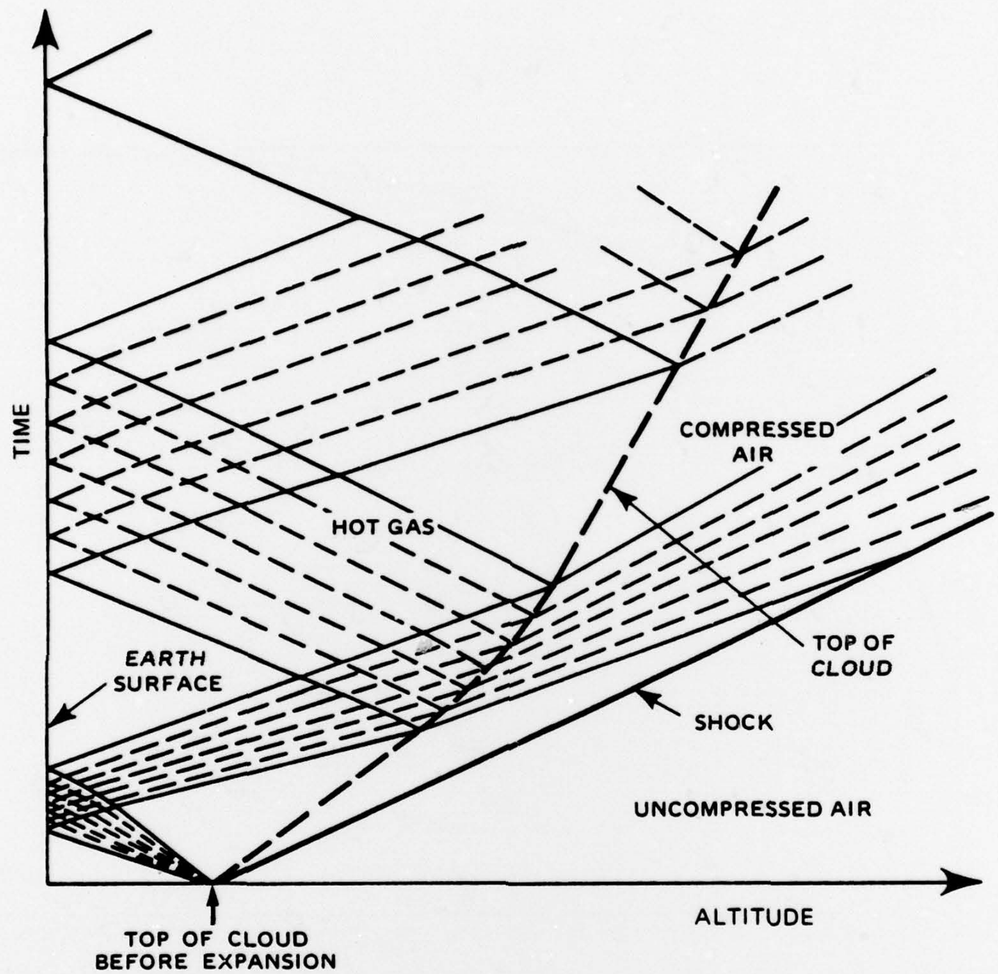

FIGURE B-1. QUALITATIVE DESCRIPTION OF ADIABATIC CLOUD EXPANSION

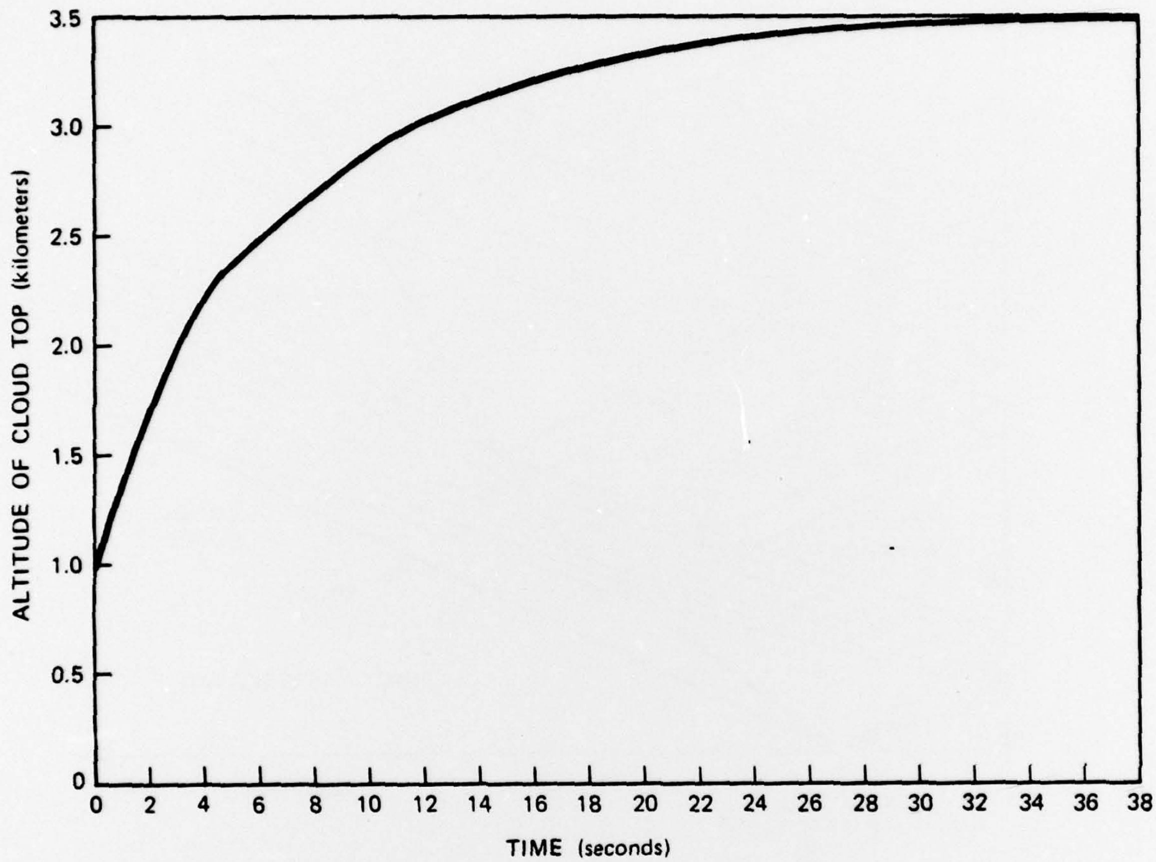

FIGURE B-2. TIME DEPENDENCE OF ADIABATIC CLOUD RISE

At time t = 0, the cloud is allowed to expand. The discontinuity in pressure at the boundary of the two gases immediately disappears with the formation of a shock wave traveling into the atmosphere and a rarefaction wave traveling toward the ground (see Figure B-1). The boundary between the cloud and the atmosphere is now a contact (or tangential) discontinuity; gas velocity (u) and pressure are continuous across this boundary, while temperature and density are discontinuous. The rarefaction wave is reflected when it meets the ground. When this reflected wave meets the contact discontinuity, it is partly transmitted and partly reflected. As this wave interacts with the contact discontinuity, it lowers the gas velocity and hence slows the motion of the boundary. After several (or more precisely, after an infinite number of) reflections, the contact discontinuity is stationary; the transmitted rarefaction waves have destroyed the initial shock; the cloud and outside atmosphere are in pressure equilibrium.

The above is, in reality, the classical shock tube problem and can be solved by the method of characteristics.[1] The results of this calculation are shown in Figure B-2. Unfortunately, the analogous problem of the radial motion of an infinitely long cylinder cannot be solved in the same way because of the explicit presence of radius and time in the equation of continuity instead of simply derivatives with respect to those variables.

[1]R. Courant and D. Hilbert, Methods of Mathematical Physics, Volume II, Chapter 5, Interscience Publishers, Inc., 1962.

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